

CAN STELLAR DYNAMICS EXPLAIN THE METALLICITY DISTRIBUTIONS OF PRESOLAR GRAINS?

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Received 1998 December 4; accepted 1999 July 8

ABSTRACT

The majority of presolar circumstellar SiC and Al₂O₃ grains found in meteorites are inferred to have originated in asymptotic giant branch (AGB) stars that were more metal-rich than the Sun despite being much older than the Sun. We test the suggestion of Clayton that this reflects the overwhelming diffusion of AGB stars from the more metal-rich inner Galaxy to the protosolar cloud. Weighting the orbital diffusion model of Wielen, Fuchs, & Dettbarn to take into account the higher density of AGB stars and molecular clouds in the inner Galaxy, we find that most parent stars of presolar grains should have diffused to the presolar cloud from their birthplaces at smaller Galactocentric radii. However, the majority of these stars are expected to have had subsolar metallicities, in conflict with the grain data. The self-consistency of the diffusion model is discussed in the context of stellar abundance data in the solar neighborhood. The disagreement between the model predictions and the observations might indicate that the inferred metallicities of presolar grain parent stars are wrong, that the adopted diffusion parameters are incorrect, and/or that stellar orbital diffusion is not the correct explanation for the grain data.

Subject headings: celestial mechanics, stellar dynamics — dust, extinction — galaxies: evolution — ISM: abundances — nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB

1. INTRODUCTION

The theory of Galactic chemical evolution (GCE) predicts that the average metallicity of the Galaxy increases with time as new generations of stars enrich the interstellar gas with heavy elements. Indeed, the detailed abundance determinations of Edvardsson et al. (1993, hereafter E93) for 189 disk dwarf stars do show such an age-metallicity relation: on average, older stars have lower metallicity. However, the most striking aspect of the E93 data set is the large scatter (~ 0.2 dex) in $[\text{Fe}/\text{H}]$ values $\{[\text{Fe}/\text{H}] = \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_{\odot}\}$ for stars of a given age. An additional difficulty for GCE models is the mounting evidence that the Sun has an atypical chemical composition for its age and position in the Galaxy. For example, the local interstellar medium apparently has about 2/3 of the solar abundances of oxygen (Meyer, Jura, & Cardelli 1998) and krypton (Cardelli & Meyer 1997), rather than the higher abundances expected from chemical evolution models. A similar situation seems to hold for carbon as well (Snow & Witt 1996) and perhaps for nitrogen (Meyer, Cardelli, & Sofia 1997). In addition, the Sun is at the high end of the $[\text{Fe}/\text{H}]$ distribution of stars of its age in the E93 sample.

The origin of the scatter in the age-metallicity relation is still unknown, but several possible explanations have been proposed. These include irregular infall of low-metallicity material onto the disk (Pilyugin & Edmunds 1996; van den Hoek & de Jong 1997), self-enrichment of star-forming regions (Malinie et al. 1993; Pilyugin & Edmunds 1996; van den Hoek & de Jong 1997), stochastic effects during Galactic evolution (Copi 1997), and the topic of the present paper, radial diffusion of stellar orbits (Francois & Matteucci 1993; Wielen, Fuchs, & Dettbarn 1996, hereafter WFD96). Stellar orbital diffusion has been long proposed as an expla-

nation for the observed increase with age of the velocity dispersions of stellar populations (e.g., Wielen 1977). It provides at least a qualitative explanation for the scatter in the age-metallicity relation, because there is observational evidence for a metallicity gradient with Galactocentric radius of about -0.1 dex kpc^{-1} . Stars born at the same time but at different Galactocentric radii thus have a spread in metallicity and if they diffuse inward or outward in the Galaxy, this will give rise to a scatter in the local age-metallicity relation of stars in a given region of the Galaxy. For example, WDF96 show that the atypically high metallicity of the Sun can be accounted for if it was born at a Galactocentric radius of 6.6 ± 0.9 kpc and has since migrated outward to its current orbit of 8.5 kpc.

An important new source of information about both GCE and stellar evolution is provided by laboratory studies of presolar stardust extracted from meteorites (see, e.g., Anders & Zinner 1993; Bernatowicz & Zinner 1997). Presolar grains are identified by their highly anomalous isotopic compositions, which indicate they formed in stellar outflows or explosions. They were a component of the molecular cloud from which the solar system formed 4.6 billion years ago and can now be isolated from meteorites by chemical treatments. The isotopic composition of each presolar grain was determined by the initial composition of its parent star, established by GCE and by the nucleosynthetic processes that occurred during the evolution of its parent. Presolar grains thus serve as detailed probes of various astrophysical phenomena.

We are concerned in this paper with presolar SiC and refractory oxide grains (primarily corundum, Al₂O₃). The majority of these types of grains are believed to have condensed in stellar winds from red giant and asymptotic giant branch (AGB) stars. The arguments for this origin are detailed elsewhere (Anders & Zinner 1993; Alexander 1993; Hoppe et al. 1994; Huss et al. 1994; Nittler et al. 1997). Shown in Figure 1 are the Si-isotopic ratios, expressed as δ -values, of typical SiC grains, known as the “mainstream”

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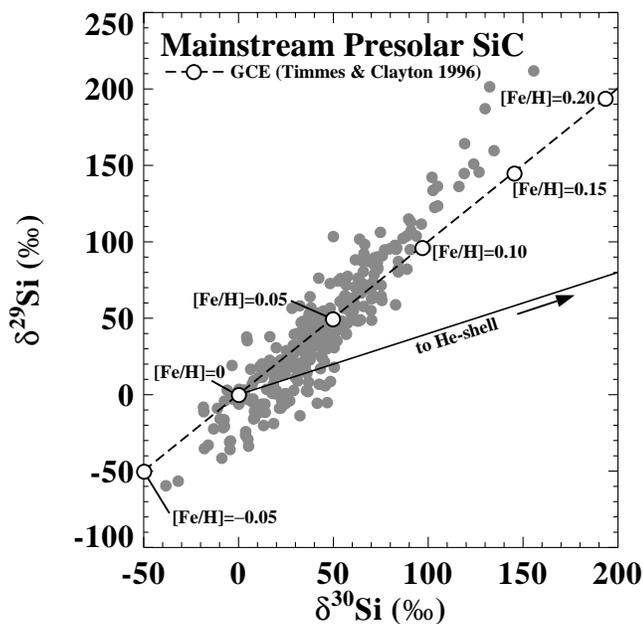


FIG. 1.—Si isotopic compositions of 300 “mainstream” presolar SiC grains from the Murchison meteorite (Alexander 1993; Hoppe et al. 1994, 1996; Alexander & Nittler 1999). Isotopic ratios are expressed as δ -values: $\delta^i\text{Si} = [({}^i\text{Si}/{}^{28}\text{Si})/({}^i\text{Si}/{}^{28}\text{Si})_{\odot} - 1] \times 1000$. The SiC grains probably formed around C-rich AGB stars that had experienced dredge-up of He-shell material into their envelopes. The slope of the mainstream trend is steeper than the slope predicted for mixing between a single initial envelope composition and the He shell (solid line). The slope is better explained if the grains’ parent stars had a range of initial envelope compositions, reflecting Galactic chemical evolution (GCE), that had been only slightly modified by the addition of He-shell material. The dashed line indicates the predicted GCE Si isotope evolution (Timmes & Clayton 1996); open circles indicate the average ISM composition for different metallicities. Most of the grains apparently originated in stars that were more metal-rich than the Sun, despite being much older.

population. The salient features of Figure 1 are that most mainstream SiC grains are enriched in the heavy isotopes of silicon, relative to the Sun, and that they lie along a line of slope ~ 1.35 . This slope is significantly different from that expected to arise from n -capture reactions during the AGB phase (~ 0.4 ; Gallino et al. 1994). The most likely explanation for this correlation line is that it reflects a spread in the initial Si-isotopic ratios of the grains’ progenitor stars, due to GCE. In fact, the detailed model of GCE by Timmes & Clayton (1996) predicts that the ${}^{29}\text{Si}/{}^{28}\text{Si}$ and ${}^{30}\text{Si}/{}^{28}\text{Si}$ ratios of the Galaxy should increase with metallicity (and hence time) along a line of slope ~ 1 on a δ -plot. This model would thus imply that most of the SiC grains originated in stars of higher metallicity than the Sun, owing to their higher-than-solar ${}^{29}\text{Si}/{}^{28}\text{Si}$ and ${}^{30}\text{Si}/{}^{28}\text{Si}$ ratios. However, since the SiC parent stars must have formed hundreds of millions to billions of years before the Sun, they would be expected from mean GCE models to be lower in metallicity. The fact that some stars that are older than the Sun have supersolar metallicity (E93) would lead from observational grounds to the expectation that some SiC progenitors would also be metal-rich, but the isotopic heaviness of most of the grains is a major puzzle.

Clayton (1997, hereafter C97) has proposed that this problem can be explained by the same mechanism of diffusion of stellar orbits that WDF96 invoked to explain the metal-richness of the Sun and the scatter in the observed

age-metallicity relation of disk stars. Just as the Sun might have migrated out from the metal-rich inner Galaxy, C97 suggests that the AGB stars that produced most mainstream SiC grains formed even further inward in Galactocentric radius than did the Sun and diffused outward before providing grains to the presolar cloud. He argues that the increase with decreasing Galactocentric radius in both the number density of AGB stars and the space density of giant molecular clouds from which AGB stars gravitationally scatter ensures that the AGB star diffusion was overwhelmingly outwards. As C97 correctly points out, if this is the explanation for the presolar SiC data then the meteoritic grains carry a “rich connection to the dynamic and chemical evolution of the Milky Way.” However, the discussion in C97 was primarily qualitative in nature and did not address the presolar oxide grain data. In this paper, we explore the orbital diffusion model in some detail to ascertain whether it can quantitatively account for the inferred metallicity distributions of both presolar SiC and Al_2O_3 grains. Our purpose is not to formulate a quantitative theory of Galactic chemodynamics but merely to test C97’s suggestion that stellar orbital diffusion is the likely explanation for the presolar SiC data, using the same models on which he based his suggestion. We also extend consideration to the presolar Al_2O_3 data.

2. METALLICITY DISTRIBUTIONS OF PRESOLAR GRAINS

Theories of nucleosynthesis and GCE make a distinction between isotopes that can be produced in stars initially consisting only of H and He (“primary” isotopes) and those the nucleosynthesis of which requires preexisting heavy elements (“secondary” isotopes). GCE models suggest that the ratio of a secondary isotope to a primary one should increase roughly linearly with time and metallicity in the Galaxy (e.g., Clayton 1988). Of relevance here are ${}^{28}\text{Si}$ and ${}^{16}\text{O}$, which are considered primary, and ${}^{29,30}\text{Si}$ and ${}^{17,18}\text{O}$, which are secondary. The Si isotope evolutionary trend calculated by Timmes & Clayton (1996) is shown on Figure 1, with open circles indicating the isotopic ratios for specific values of $[\text{Fe}/\text{H}]$. We infer the metallicities of the SiC progenitor stars from this calculation, with $[\text{Fe}/\text{H}] \approx \delta^{29}\text{Si}/1000$. Note that the calculated evolution has been “renormalized” to pass through the solar composition ($\delta^{29,30}\text{Si} = 0$) at $[\text{Fe}/\text{H}] = 0$ (Timmes & Clayton 1996), on the assumption that the Sun has Si isotopic ratios typical of the interstellar medium at the time of its birth. However, there is some evidence, based on isotopic data of both Si and Ti in presolar SiC grains, that the Sun is slightly enriched in ${}^{28}\text{Si}$, relative to the typical ISM (Alexander & Nittler 1999). If this is true, then the metallicities inferred from Figure 1 for the parent stars are overestimated by about 0.08 dex.

Figure 2 shows the O-isotopic ratios for 73 meteoritic presolar oxide grains with ${}^{16}\text{O}/{}^{18}\text{O} \leq 1700$. Also shown are the calculated O-isotopic GCE (Timmes, Woosley & Weaver 1995), again normalized to pass through the solar composition at $[\text{Fe}/\text{H}] = 0$, and the predictions of Lattanzio & Boothroyd (1997) for the envelope compositions of red giants and AGB stars of different masses and initial compositions (filled circles). These envelope compositions reflect the standard first and second dredge-up processes that occur in late-type giant stars. Note that most of the grains in Figure 2 were found by an automatic ${}^{16}\text{O}/{}^{18}\text{O}$ ratio mapping technique that is biased against finding

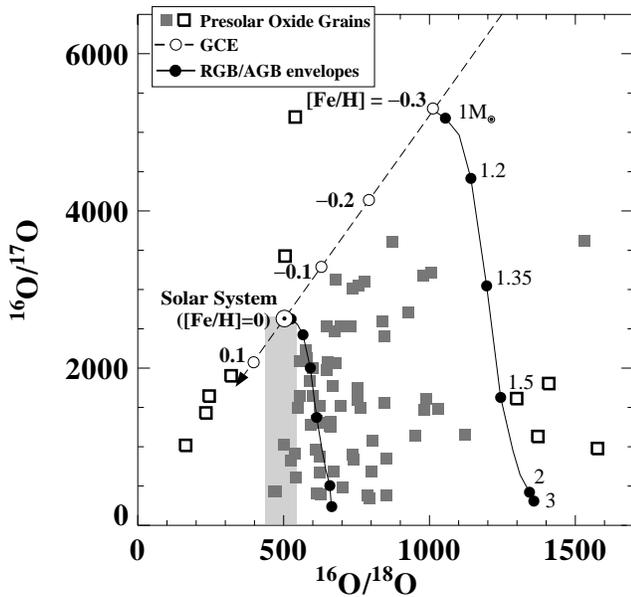


FIG. 2.—Oxygen isotopic compositions of 73 presolar Al_2O_3 grains from meteorites (Nittler et al. 1997). Filled circles show predicted envelope compositions of red giants and AGB stars of different masses and metallicities (Lattanzio & Boothroyd 1997). The dashed line is the predicted GCE O isotope trend of Timmes et al. (1995), normalized to go through solar; open circles indicate the average ISM composition for different metallicities. The filled squares indicate grains that most likely formed in red giants and AGB stars and whose initial metallicities can be reliably inferred from the models. Open squares represent grains whose origin is less clear and whose metallicities cannot therefore be estimated. Many presolar oxides have compositions that lie in the gray region and are missing from the data set owing to a sampling bias.

grains with $^{16}\text{O}/^{18}\text{O}$ ratios within about 10% of the solar value of 500. Nittler et al. (1997) measured all three stable O isotopes in ~ 400 meteoritic grains and found that as many as half of the presolar grains present in the studied meteorites have $^{16}\text{O}/^{18}\text{O}$ ratios within $\sim 10\%$ of solar and ^{17}O enrichments (shaded region in Fig. 2) and have hence been missed. The majority of the observed grains (*gray squares*) have $^{16}\text{O}/^{18}\text{O}$ ratios from ~ 1 – 2 times the solar ratio. These grains are well explained by the GCE and dredge-up models; their parent stars' masses and metallicities can be directly inferred by interpolation or extrapolation of the dredge-up calculations. We only consider these grains in our estimate of the oxide parent metallicity distribution. This is both because these grains dominate the data set, particularly when the sampling bias described above is considered and because the origins of the other grains (*open squares* and several additional grains with $^{16}\text{O}/^{18}\text{O} > 1700$) are not as clear (e.g., Nittler et al. 1997), and inferring their metallicities is hence less straightforward.

Our best estimates of the metallicity distributions of the parent stars of presolar SiC and oxide grains are shown in Figure 3. The dark distributions represent the observed grains from Figures 1 and 2, whereas the light gray oxide metallicity distribution represents an estimate of the distribution for grains missed by automatic $^{16}\text{O}/^{18}\text{O}$ searches. This distribution was estimated by assuming that 100 grains were missing from the data set and randomly assigning each an O-isotopic composition within the shaded region of Figure 2. The metallicities were then inferred for the assigned compositions using the same stellar models used to infer metallicities for the observed grains. The metallicity dis-

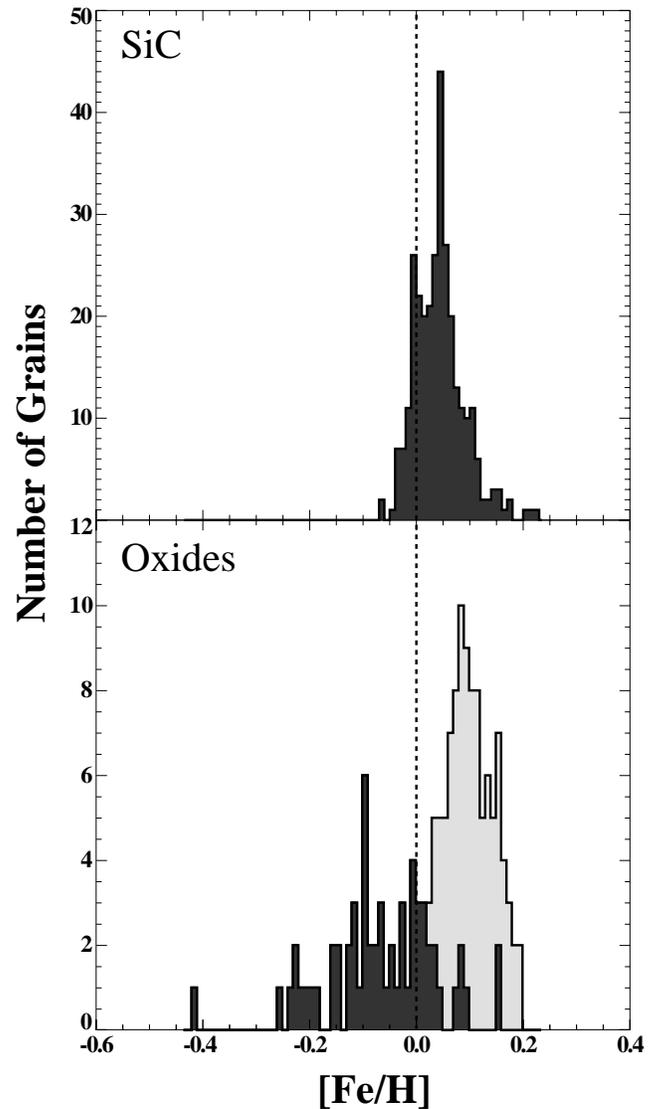


FIG. 3.—Histograms of the inferred metallicities of the mainstream SiC grains (Fig. 1) and most presolar oxide grains (*filled squares* in Fig. 2). The dark histograms indicate the observed grains. The light oxide histogram indicates an estimate for the 50% of grains that are missed by the ion mapping technique employed to find most of the grains. The oxides clearly came from stars with a wider scatter in $[\text{Fe}/\text{H}]$ than did the SiC grains. More problematic is the observation that most SiC grains, and possibly most oxide grains, apparently came from higher than solar metallicity stars, yet the grains' parent stars must have formed hundreds of millions to billions of years before the solar system formed.

tributions are clearly different for the SiC and the oxides. The oxide distribution is considerably wider than that of SiC (standard deviations of 0.1 and 0.05, respectively) and extends to lower metallicity. Nonetheless, with the assumptions used to infer the distributions, a major fraction of both types of presolar grain seem to have originated in stars of higher than solar metallicity.

3. DIFFUSION MODEL

We adopt here the basic physical picture outlined by WFD96 and C97. We assume that the composition of the interstellar gas is uniform at a given time and Galactocentric radius but that there are gradients in $[\text{Fe}/\text{H}]$ with radius, R , and age, τ , the magnitudes of which we denote α

and β , respectively. Following WFD96, we take α to be $-0.09 \text{ dex kpc}^{-1}$, assumed for simplicity to be independent of time, and β to be $-0.048 \text{ dex Gyr}^{-1}$, based on a fit to the data of E93. The complete age-metallicity- R_i relation is then given by

$$[\text{Fe}/\text{H}] = 0.815 - 0.048\tau - 0.09R_i. \quad (1)$$

In this equation, R_i is the initial Galactocentric radius (in kpc) of a star born $\tau \times 10^9$ yr ago. WFD96's proposed birthplace of the Sun at $R_{i,\odot} = 6.6$ kpc follows immediately from equation (1) by setting $[\text{Fe}/\text{H}] = 0$ and $\tau = 4.6$. Equation (1) is plotted in Figure 4 for $\tau = 0, 4.6, 6.0,$ and 12 Gyr, analogous to Figure 2 of C97. Also shown schematically is the proposed diffusion of the Sun from the appropriate $[\text{Fe}/\text{H}]-R$ curve 4.6 Gyr ago to its present position and the diffusion of two presolar AGB stars, born 6 Gyr ago, from the inner Galaxy to the birthplace of the Sun. AGB star A is similar to the example stars of C97; it has diffused 2 kpc in its lifetime and has a metallicity that is higher than solar. Star B has diffused a much smaller distance (< 1 kpc) and has a solar metallicity.

The orbital diffusion model of Wielen (1977) and WFD96 predicts that stars born at a given Galactocentric radius, R_i , will diffuse such that they will have a rms spread in R after a time t (in 10^9 yr) given by

$$\sqrt{\langle(\Delta R)^2\rangle} = \sqrt{\langle(R - R_i)^2\rangle} = 0.92 \times \sqrt{t}. \quad (2)$$

Viewed locally, the diffusion should be approximately isotropic ($\langle\Delta R\rangle = 0$), with equal numbers of stars diffusing inward and outward in R . We assume the simplest case of one-dimensional diffusion with a constant isotropic diffusion coefficient. In this case, after time t the radial distribu-

tion of stars born at $R = R_i$ will be described by a Gaussian with a mean value of R_i :

$$N = \frac{1}{\sigma(t)\sqrt{2\pi}} e^{-(R - R_i)^2/2\sigma(t)^2}. \quad (3)$$

The standard deviation of the distribution is given by equation (2), $\sigma(t) = 0.92\sqrt{t}$. Numerical calculations of stellar diffusion in velocity space suggest that Gaussian diffusion profiles are a reasonable approximation (Jenkins & Binney 1990). Note that, by symmetry, equation (3) describes, after time t , both the distribution of R values of stars born at a fixed R_i and the distribution of birth radii, R_i of stars present at a fixed radius R .

As discussed above, however, C97 argued that when viewed on a Galactic scale, the diffusion should not be isotropic, since the number density of AGB stars and of molecular clouds (from which the stars were assumed to gravitationally scatter) increase rapidly with decreasing R . To take this suggestion into account, we assume that the density of stars and of clouds both decrease exponentially with increasing R . Equation (3) is then weighted with the function $e^{-R_i/R_{\text{disk}}}$ to yield an expression for the number of stars that have diffused from R_i to a specific value of R in time t :

$$\begin{aligned} N(R_i, t) &= \frac{C_1}{\sigma(t)\sqrt{2\pi}} e^{-(R_i/R_{\text{disk}}) - [(R_i - R)^2/2\sigma(t)^2]} \\ &= \frac{C_1}{\sigma(t)\sqrt{2\pi}} e^{-(R_i/R_{\text{disk}})} e^{\sigma(t)^2/(2R_{\text{disk}})^2} e^{-[R_i - R_{\text{max}}(t)]^2/2\sigma(t)^2}, \end{aligned} \quad (4)$$

where $\sigma(t)$ is given above and $R_{\text{max}}(t) = R - \sigma(t)^2/R_{\text{disk}}$. C_1 is a constant used to normalize the distribution to the total number of stars in the system. Its value is unimportant here since we are concerned with the relative numbers of stars from different R_i , not the overall normalization. The parameter R_{disk} is a measure of the asymmetry in the diffusion due to gradients in the density of both AGB stars and molecular clouds. Its value is discussed below. The second equality shows explicitly that the distribution remains Gaussian in R_i with the same width as the nonweighted case, but with a mean value, R_{max} , that is shifted inward by $\sigma(t)^2/R_{\text{disk}}$ kpc. The inward shift in the maximum of the distribution makes clear the fact that more stars diffuse outward than inward in this case.

Because presolar grains formed during the AGB phase of their parent stars, and the AGB phase is very short compared to the entire lifetime of a star, we assume that the presolar grain parent stars ended their lives 4.6 billion years ago at $R = R_{i,\odot} = 6.6$ kpc, the birthplace of the Sun inferred from equation (1). Because the production of micron-sized circumstellar grains might depend on stellar mass, we consider stars of varying initial mass m (in M_\odot) with lifetimes $t(m)$ calculated from the metallicity-independent mass-age relation of Scalo (1986):

$$\log_{10} t(m) = 10.0 - 3.6 \log_{10} m + (\log_{10} m)^2. \quad (5)$$

The most probable birthplace of stars of mass m that ended their lives at the time and place of the birth of the solar system is the Galactocentric radius for which equation (4)

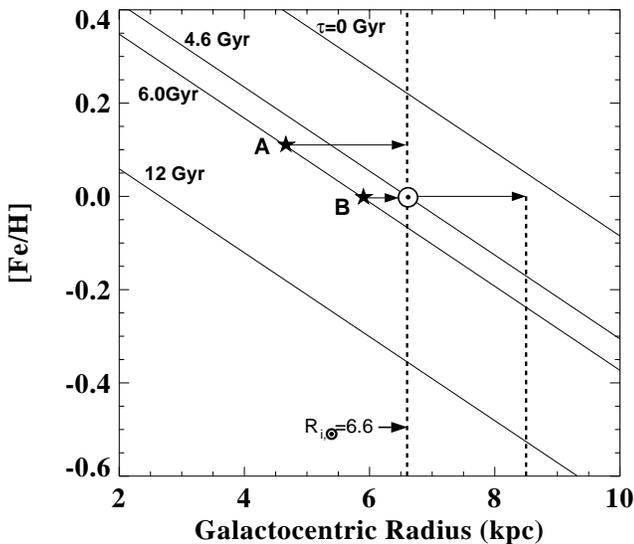


FIG. 4.—Schematic representation of the orbital diffusion of the Sun and of two presolar AGB stars. The solid lines, given by eq. (1), represent the gradient of $[\text{Fe}/\text{H}]$ with Galactocentric radius today ($\tau = 0$) and at three times in the past. The Sun is postulated to have been born at $R_{i,\odot} = 6.6$ kpc and migrated to its present position at $R = 8.5$ kpc. Similarly, the AGB stars were born 1.5 Gyr before the Sun and migrated to the solar birthplace where they provided presolar grains to the protosolar cloud. Star A diffused 2 kpc and is more metal-rich than the Sun, while star B diffused < 1 kpc and has solar metallicity.

has its maximum value, i.e., R_{\max} , with $R = R_{i,\odot} = 6.6$ kpc:

$$R_{\max}(m) = 6.6 - \frac{(0.92)^2 t(m)}{R_{\text{disk}}}. \quad (6)$$

Because equation (4) is symmetric in R_i , $R_{\max}(m)$ is also the average value of R_i for the presolar grain parent stars. Setting $R_i = R_{\max}(m)$ and $\tau = 4.6 + t(m)$ in equation (1) then yields the average value of $[\text{Fe}/\text{H}]$ expected for presolar grain parent stars of mass m :

$$[\text{Fe}/\text{H}] = \left(\frac{0.076}{R_{\text{disk}}} - 0.048 \right) t(m) \pm 0.083 \sqrt{t(m)}. \quad (7)$$

The uncertainty in this equation indicates the expected 1σ scatter in $[\text{Fe}/\text{H}]$ as a function of time (mass). This term follows from the diffusional spread in R_i (eq. [2]) and the Galactic gradient in metallicity α (see eq. [10] of WFD96): $\sigma_{[\text{Fe}/\text{H}]} = |\alpha| \sigma_R$. Equation (7) shows that weighting the diffusion profiles makes the age-metallicity gradient of stars shallower than the original slope of the interstellar gas (see eq. [1]).

The parameter R_{disk} in the above equations is defined by

$$1/R_{\text{disk}} = 1/R_* + f/R_{\text{MC}}, \quad (8)$$

where R_* and R_{MC} denote exponential scale lengths for AGB stars and molecular clouds (MCs), respectively, and the weighting factor f is described below. An exponential stellar density profile is generally accepted, but there is significant uncertainty in the exact value of the scale length (e.g., Prantzos & Aubert 1995). We take a representative estimate of R_* to be 4 kpc. The observed radial distribution of MCs, inferred from CO observations, has a maximum at $R \sim 3$ kpc (the ‘‘molecular ring’’), but the distribution outside this radius can be fitted well by an exponential with scale length $R_{\text{MC}} \sim 3$ kpc (Blitz 1997). The factor of f in equation (8) allows us to vary the influence of MCs on the results. This factor is included because the validity of C97’s assumption that MCs are the primary cause of the radial diffusion is not clear.

The original evidence for the orbital diffusion of stars was the observation that the velocity dispersions of stellar populations increase with age (e.g., Wielen 1977). However, the numerical study by Lacey (1984) has shown that gravitational scattering of stars by molecular clouds leads both to a slower increase in velocity dispersion with age than is observed and to a higher ratio of vertical (out of the Galactic plane) to radial scattering than is observed. These results were borne out by the study of Jenkins & Binney (1990), who included scattering both by clouds and by spiral inhomogeneities in the overall gravitational potential of the Galaxy. They found that scattering by MCs is indeed insufficient to explain the stellar velocity dispersion data and that the effects of stochastic spiral structure are important for the scattering of stars, particularly in the plane of the disk. Therefore, the radial diffusion of stars that we are considering here might be primarily caused not by scattering off of molecular clouds, but rather by spiral effects, for which there is no obvious reason to expect a strong radial dependence. We will consider here the two limiting cases $f = 1$ and 0 ($R_{\text{disk}} = 1.7$ and 4 kpc). In the first case, the diffusion process is assumed to be dominated by scattering off molecular clouds. In the second case, the diffusion is assumed to be due to spiral structure and hence the radial distribution of molecular clouds does not weight the diffusion of AGB stars.

Note that we will not attempt here to predict an overall histogram of $[\text{Fe}/\text{H}]$ values for the parent stars of presolar grains. Such a prediction would require integrating equation (7) over a range of stellar masses, taking into account (1) the initial mass function, which gives the mass spectrum of new stars; (2) knowledge of the relative production of micron-sized circumstellar grains by AGB stars of different masses and metallicities; and (3) the time-dependent terms multiplying the Gaussian in equation (4). In principle, equation (2) could be estimated from the inferred masses and metallicities of the presolar oxide grains. However, such an estimate would undoubtedly be so uncertain as to be of little value, particularly since the data set is strongly biased.

4. PREDICTED METALLICITY DISTRIBUTIONS

The predicted trends of metallicity versus Galactocentric radius and stellar mass are illustrated in Figure 5 for the extreme case where the orbital diffusion is weighted by both AGB stars and molecular clouds ($f = 1$, $R_{\text{disk}} = 1.7$). In Figure 5a, the filled symbols represent the average $[\text{Fe}/\text{H}]$ values for presolar grain progenitor stars of different masses plotted against their most probable birth radii (R_{\max} ; eq. [6]). The open symbols connected by thin dashed lines are the expected $\pm 1 \sigma$ ranges in $[\text{Fe}/\text{H}]$ and R_i for each stellar mass. The average $[\text{Fe}/\text{H}]$ versus stellar mass trend is shown as the middle solid curve in Figure 5b; the outer (*thick-dashed*) curves are the $\pm 1 \sigma$ scatter in $[\text{Fe}/\text{H}]$ given by equation (7). Plotted as filled circles are the masses and metallicities of presolar oxide grain parents, inferred from Figure 2. The range of inferred SiC parent metallicities is indicated by the shaded region, with different levels of shading denoting relative numbers of SiC grains with the corresponding $[\text{Fe}/\text{H}]$ values. The dotted region shows the range of metallicities expected for most of the ‘‘missing’’ oxide grains (§ 2; Fig. 3).

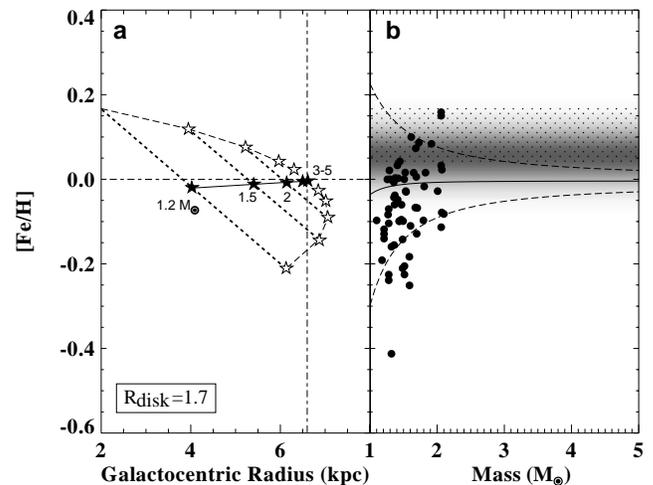


FIG. 5.—Results of the diffusion model for $R_{\text{disk}} = 1.7$ case (weighting by stars and molecular clouds). (a) Filled symbols: average $[\text{Fe}/\text{H}]$ vs. average Galactocentric radius at stellar birth (R_{\max}) for presolar grain parent stars of masses 1.2 – $5 M_{\odot}$ (see eqs. [6] and [7]). Open symbols: $\pm 1 \sigma$ scatter in $[\text{Fe}/\text{H}]$ and R_i for different masses. (b) Solid curves: average value and $\pm 1 \sigma$ ranges in $[\text{Fe}/\text{H}]$ vs. stellar mass. Filled circles: inferred masses and metallicities of presolar oxide grains (Fig. 2). Dotted region: range of $[\text{Fe}/\text{H}]$ expected for oxide grains missing from the data set owing to a sample bias. Shaded region: range of inferred metallicities of SiC grain parent stars; gray level is proportional to number of grains in appropriate $[\text{Fe}/\text{H}]$ bin.

Clearly, weighting the orbital diffusion according to the increased number of stars and molecular clouds in the inner Galaxy has a major effect on the birthplaces of stars that could have provided dust to the presolar cloud. Many more stars diffuse outwards in the Galaxy than do inwards, and the distances that stars diffuse can be large. For example, stars of mass $1.5 M_{\odot}$ will have diffused an average distance of 1.3 kpc during their 2.5 Gyr lifetime. Moreover, about 80% of such stars will have been born inside $R = 6.6$ kpc, and $\sim 19\%$ will have been born inside $R = 4$ kpc. As predicted by C97, the overwhelmingly outward diffusion allows there to be many presolar AGB stars with higher than solar metallicity present at the time and place of the formation of the solar system. However, it is clear from Figure 5 that such stars will not dominate the distribution; a great number of stars diffusing outward in R will have metallicities lower than solar. Hence, although the $[\text{Fe}/\text{H}]$ versus mass curves in Figure 5b agree remarkably well with the observed oxide grain distribution (*filled circles*), the model does not predict metallicity distributions like those inferred from the SiC and “missing” oxide data, i.e. dominated by higher-than-solar-metallicity stars. In fact, equation (7) shows that the average value of $[\text{Fe}/\text{H}]$ is less than zero for all stars, as long as $R_{\text{disk}} \geq 1.6$. Our assumed value of $R_{\text{disk}} = 1.7$ is close to this limit, so the average metallicity is close to solar for all masses and the overall predicted distribution of metallicity versus mass is approximately symmetric about $[\text{Fe}/\text{H}] = 0$ (Fig. 5).

As discussed in the previous section, there is some evidence that the observed diffusion of stellar orbits is not caused primarily by gravitational interactions with giant molecular clouds, but rather by collective effects in the disk itself. We hence consider the case where the diffusion is weighted only by the increased concentration of stars in the inner Galaxy, but not by the increased number of clouds, i.e. $f = 0$, $R_{\text{disk}} = 4$. The results are shown in Figure 6; the meaning of the symbols is the same as in Figure 5. As in the previous case, weighting the orbital diffusion profiles results in a majority of presolar grain parent stars having formed inward in the Galaxy from the Galactocentric radius of the presolar cloud. Because the weighting is less severe in this case, however, the typical distances diffused are smaller and the average $[\text{Fe}/\text{H}]$ values predicted by equation (7) are

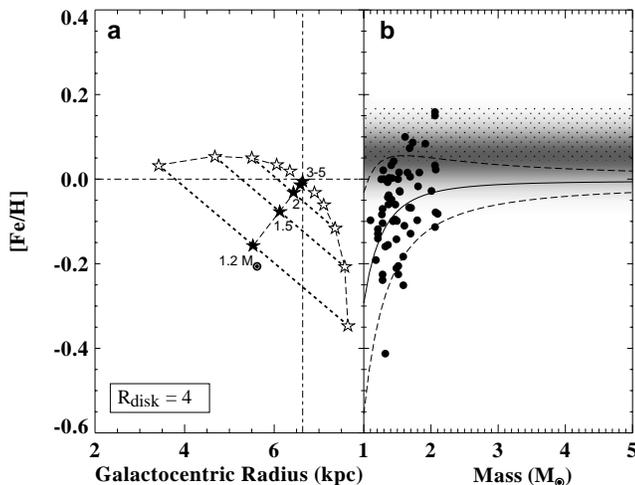


FIG. 6.—Results of the diffusion model for $R_{\text{disk}} = 4$ case (weighting by stars only). See Fig. 5 for explanation of symbols.

lower. In fact, this model predicts that the 1σ upper $[\text{Fe}/\text{H}]$ trend should have a maximum value of ~ 0.05 (for stars of mass $\sim 1.5 M_{\odot}$). This is in sharp contrast to the $R_{\text{disk}} = 1.7$ case, where the 1σ upper $[\text{Fe}/\text{H}]$ range increases continuously with decreasing stellar mass, at least down to $1 M_{\odot}$.

As stated above, we do not attempt to integrate equation (7) to yield a histogram of presolar grain $[\text{Fe}/\text{H}]$ values. Nevertheless, it is clear from Figures 5 and 6 that neither model predicts that presolar grains should have originated overwhelmingly from stars of higher metallicity than the Sun. This is the major result of this paper and will be discussed further below.

5. SELF-CONSISTENCY?

It should be pointed out that the model presented above is not entirely self-consistent. The inconsistency arises because we have used the observed age-metallicity gradient from the E93 data set as the age-metallicity gradient of the interstellar gas from which stars form. But if a major fraction of the E93 stars have diffused outward in Galactocentric radius since they formed, they will show a shallower age-metallicity gradient than the true gradient in the gas. Equation (7) shows that, following the outward diffusion, all stars should share the same age-metallicity gradient, regardless of their Galactocentric radius. Hence a self-consistent model will predict that the presolar grain parent stars have the same age-metallicity gradient as that determined from the E93 observations, i.e., $\beta = -0.048$ dex Gyr^{-1} . The resulting $[\text{Fe}/\text{H}]$ versus mass curves are shown in Figure 7. These curves are similar to the $R_{\text{disk}} = 4$ case (Fig. 6), but in this case, an even smaller fraction of the parent stars is predicted to have higher than solar metallicity.

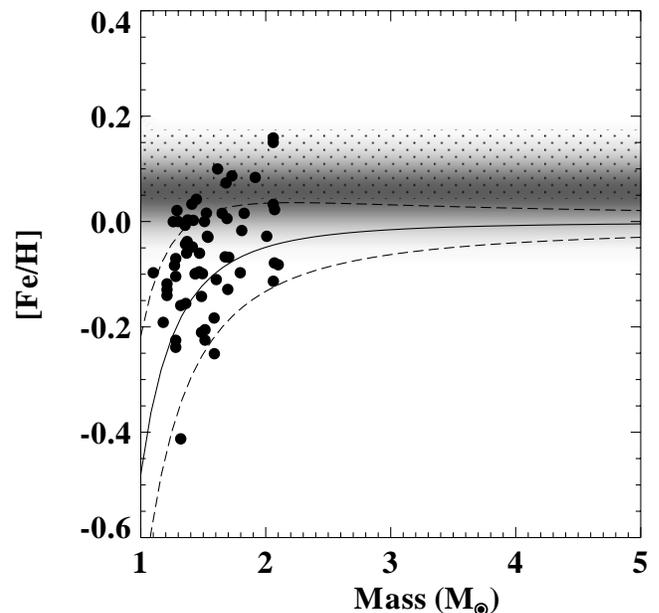


FIG. 7.—Predicted $[\text{Fe}/\text{H}]$ vs. stellar mass trend for the self-consistent diffusion model described in § 5. In this case, the age-metallicity gradient of the interstellar gas is shifted such that the age-metallicity gradient of presolar grain parent stars after diffusion is the same as that observed by E93 for stars in the solar neighborhood. Symbols are the same as in Fig. 5b and 6b. The $[\text{Fe}/\text{H}]$ -mass trends are the same for all values of R_{disk} .

Let us examine further the ramifications of performing the calculation self-consistently. Equation (7) implies that in order for the age-metallicity gradient of stars to be -0.048 dex Gyr^{-1} , the gradient for the interstellar gas must be $\beta = -0.048 - 0.076/R_{\text{disk}}$. If we take $R_{\text{disk}} = 1.7$ (weighting by molecular clouds and stars), $\beta = -0.093$ and equation (1) implies that the Sun was born at $R_{i,\odot} = 4.3\text{kpc}$. For $R_{\text{disk}} = 4$ (weighting by stars only), we find $\beta = -0.067$ and the Sun formed at 5.6 kpc.

There are a number of difficulties with the self-consistent model. First, WFD96 argue both that the self-gravity of the disk might keep the orbital diffusion from being overwhelmingly outward and that weighting the diffusion profiles as we have done gives implausible results for the inferred birthplaces of the stars in the E93 sample. Second, for both values of R_{disk} considered above, equation (3) suggests that the probability of the Sun having migrated at least as far as is required by the self-consistent model is $\sim 17\%$. While nonnegligible, this low probability makes orbital diffusion less attractive as an explanation for the high metallicity of the Sun. Third, the inferred metallicity gradients of -0.093 and -0.067 dex Gyr^{-1} are considerably steeper than predicted by current GCE models for the mean ISM. For example, the $[\text{Fe}/\text{H}]$ -age relation calculated by Timmes et al. (1995) can be fitted (for $\tau \lesssim 10$ Gyr) to a linear function with slope ~ -0.02 dex Gyr^{-1} . To summarize, performing the weighted diffusion calculation so that the stars observed today in the solar neighborhood are treated in the same fashion as the AGB stars that produced presolar grains results both in poor agreement between the predicted metallicities of presolar AGB stars and the presolar grain data, and in physically implausible results for the diffusional distance of the Sun and other nearby stars.

6. DISCUSSION AND CONCLUSIONS

The major result of this work is that, when weighted to take into account the higher density of stars and/or molecular clouds in the inner Galaxy, the orbital diffusion model of WFD96 does not predict that most presolar grain parent stars should have had metallicities higher than solar. This is in contrast to the main prediction of C97. If the postulated orbital diffusion indeed occurred, then we must consider possible explanations for the discrepancy between the model and the observations.

First, perhaps the inferred metallicities of presolar grains are incorrect and their true metallicities are not overwhelmingly higher than solar. As discussed in § 2, there is some evidence that the Sun is slightly rich in ^{28}Si , relative to the average $[\text{Fe}/\text{H}] = 0$ interstellar medium (Alexander & Nittler 1999). If correct, the metallicities of the SiC grain parent stars have been overestimated by perhaps 0.08 dex. If the SiC $[\text{Fe}/\text{H}]$ distribution is shifted downward by this amount, the agreement between the diffusion predictions and the SiC data is much improved. Figures 5–7 show that the predicted curves are already in good agreement with the observed oxide grains. However, the metallicities estimated for the major fraction of presolar oxides, those grains missing from the data set because of a sampling bias, are still all higher than solar and in poor agreement with the diffusion model. There are few constraints on the O-isotopic evolution of the Galaxy, but observations of molecular clouds suggest that the Sun is anomalously high in its abundance of ^{18}O (Penzias 1981; Wilson & Rood 1994). Renormalizing the inferred metallicities of the presolar oxide

grains to agree with the molecular cloud observations would have the effect of *increasing* the oxide $[\text{Fe}/\text{H}]$ values, perhaps by as much as 0.2 dex, in clear disagreement with both the SiC data and the diffusion model. Ti-isotopic data from presolar oxide grains could help resolve this issue, because the evolution of Ti isotopes is constrained by the SiC data (Alexander & Nittler 1999). A few presolar oxide grains with precise Ti data suggest that the oxide normalization used in Figure 3 is approximately correct (Huss, Fahey, & Wasserburg 1995; Choi et al. 1998; Alexander & Nittler 1999), but additional data are highly desirable.

Second, the inferred metallicities might be correct and orbital diffusion the explanation for the distributions, but one or more of the assumptions behind the specific model discussed here could be wrong. For example, we have assumed in our model that the presolar grains formed in stars taken at random from the population of stars present at $R = 6.6$ kpc at the time of solar formation, but there may be processes that favor grains from the higher-metallicity stars. One obvious possibility is that stars of higher metallicity produce more dust grains than do those of lower metallicity, owing to their higher abundance of condensable atoms. Assuming that AGB star dust production is linearly proportional to Fe/H , we find that an additional term of magnitude $\sim 0.016t(m)$ should be added to the average $[\text{Fe}/\text{H}]$ as a function of stellar mass given by equation (7). Although this term indeed implies an upward shift in $[\text{Fe}/\text{H}]$ values for the parent stars of presolar grains, it does not shift the overall distribution to supersolar metallicities.

Alternatively, we have assumed diffusion parameters (e.g., R_{disk}) based on observations of the Galaxy today, but these might be inappropriate for the Galaxy billions of years ago. For example, the density of both AGB stars and molecular clouds might have dropped off with Galactocentric radius more steeply in the past. This would imply smaller values of R_{disk} than we have considered here, with the result that a larger fraction of presolar grain parent stars could have been more metal-rich than the Sun. However, as discussed in the previous section, it is already difficult to reconcile the weighted diffusion model (with our assumed R_{disk} values) with astronomical observations of stars in the solar neighborhood. If we require even stronger outward diffusion to understand the presolar grain data, the inconsistency is exacerbated. One way out of this problem would be to argue that while today the orbital diffusion is apparently isotropic in Galactocentric radius, 4.6 Gyr ago it was overwhelmingly outward. There is certainly no compelling astronomical evidence for such a radical change in stellar dynamics over the relevant timescale. For example, in this scenario one might expect some clear difference (in age-metallicity slope, for instance) in the E93 data between young stars and those older than the Sun. It thus seems likely that, at least in first approximation, any orbital diffusion that affected the presolar grain parent stars should be qualitatively similar to any diffusion affecting stars today in the solar neighborhood. By the arguments presented in the previous section, it seems far from clear that the outward diffusion envisioned by C97 is likely to have occurred.

The C97 model for outward diffusion of AGB stars took as reasonable parameters those derived by WFD96 to explain the observed scatter in the elemental abundances of nearby stars and for the anomalously high metallicity of the Sun. For our testing, we have hence assumed in this paper that the WFD96 model is valid and is indeed the correct

explanation for the observed scatter in the elemental abundances of nearby stars and for the anomalously high metallicity of the Sun. However, several arguments have been put forward against stellar orbital diffusion as the main cause of the age-metallicity scatter (e.g., E93; Pilyugin & Edmunds 1996; van den Hoek & de Jong 1997). First, it is not obvious that the magnitude of the metallicity scatter increases with age. Although WFD96 show a systematic increase in $\sigma_{[\text{Fe}/\text{H}]}$ with stellar age for the E93 data set (see their Fig. 4), we find that this result depends strongly on the binning used. Second, if the observed spread in both $[\text{Fe}/\text{H}]$ and $[\text{O}/\text{H}]$ and the observed radial gradients in these quantities are taken into account, the two elements imply significantly different R_i values for the stars in the E93 sample (van den Hoek & de Jong 1997). Third, the scatter in elemental abundances in H II regions, similarly aged open clusters, and very young B stars at a given Galactocentric radius can be very large (Pilyugin & Edmunds 1996; van den Hoek & de Jong 1997). We note that the reasonably good agreement between the orbital diffusion model and the observed oxide grain distribution is not strong evidence that the diffusion took place, only that these grains formed in stars with a somewhat typical range of metallicities for their age, whatever the cause of that metallicity spread.

Finally, one important factor we have not considered here is that the Milky Way is probably barred (Binney & Merrifield 1998). The effects of a bar are likely to dramatically change the simple picture of orbital dynamics discussed here and by WFD96 and C97. Raboud et al. (1998) have discussed two possible types of orbits in a barred potential: (1) orbits confined to the bar, and (2) so-called

“hot” orbits where stars chaotically migrate from inside the bar to outside. Furthermore, these authors suggest that many old disk stars in the solar neighborhood indeed originated in the inner Galaxy and are on bar-induced “hot” orbits. This suggestion is based on the fact that these stars are, on average, moving outward in Galactocentric radius. At first glance, this might seem to favor the model of C97 with the effects of the bar replacing those of giant molecular clouds. However, such “hot” stars do not dominate the population of stars in the solar neighborhood. Also, the observed metallicity distribution of the “hot” stars in the Raboud et al. sample is centered on solar and ranges from ~ -0.5 to $\sim +0.5$ dex. Stars scattered outward to the solar neighborhood today are thus not overwhelmingly metal-rich with respect to the Sun and we might expect a similar result for the presolar grain parent stars, even if their orbits were also strongly influenced by a Galactic bar.

In summary, given both the large uncertainties involved in inferring the metallicities of presolar grain parent AGB stars and the lack of compelling evidence that most stars typically diffuse large distances outward in Galactocentric radius, we think it is premature to conclude that orbital diffusion is the correct explanation for the isotopic heaviness of presolar SiC grains found in meteorites. Presolar grains clearly carry a fingerprint of Galactic evolution, but attempts to decode their information are far from complete.

The authors would like to thank François Schweizer and the referee, Don Clayton, for helpful comments. This work was partially funded by NASA grant NAG5-4328.

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